

Control of two-atom entanglement with two thermal fields in coupled cavities

Li-Tuo Shen,¹ Zhen-Biao Yang,² Huai-Zhi Wu,¹ Xin-Yu Chen,¹ and Shi-Biao Zheng^{1,†}

¹*Lab of Quantum Optics, Department of Physics,
Fuzhou University, Fuzhou 350002, China*

²*Key Laboratory of Quantum Information,
University of Science and Technology of China, Chinese Academy of Sciences, Hefei
230026, China*

[†]*Corresponding author: sbzheng11@163.com*

The dynamical evolution of a quantum system composed of two coupled cavities, each containing a two-level atom and a single-mode thermal field, is investigated under different conditions. The entanglement between the two atoms is controlled by the hopping strength and the detuning between the atomic transition and the cavities. We find that when the atomic transition is far off-resonant with both the eigenmodes of the coupled cavity system, the maximally entangled state for the two atoms can be generated with the initial state in which one atom is in the ground state and the other is in the excited state. When both the two atoms are initially in the excited state, the entanglement exhibits period sudden birth and death. By choosing appropriate parameter values, the initial maximal entanglement of the two atoms can be frozen. The relation between the concurrence and cooperative parameter is calculated. © 2012 Optical Society of America

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1. Introduction

Quantum system inevitably interacts with the surrounding heat environments, i.e., thermal fields. The thermal field, which is emitted from a source in thermal equilibrium, has become an important topic in quantum theory of damping and quantum experiment of laser [1]. Under the condition of constant average energy, the thermal field maximizes the entropy

of the field and is always considered to be chaotic [2]. However, Bose *et al.* [3] showed that a single two-level atom and a thermal field could be entangled due to their linear interaction. Recently, the model in which two atoms interact with a single-mode thermal field has attracted great interest [4–10]. Kim *et al.* [4] considered two identical two-level atoms which are resonantly coupled to a single-mode thermal field and found the field could entangle two atoms which are initially in a separate state, while Zhang [5] generalized Kim’s idea to the case that two atoms are slightly detuned from the thermal field. El-Orany [6] gave a exact treatment for entanglement between two atoms when they interact simultaneously with a single-mode thermal field through multiphoton exchange. On the other hand, the fundamental dissipative process of the radiation field inside a cavity may be understood from a simple model where the mode of interest is coupled to a multi-mode thermal reservoir. There have been some studies devoted to the influence of thermal noise on the behavior of different quantum system [11–16] and to the possibility of the quantum information processing via thermal fields [17–19]. However, previous theoretical schemes and experiments focus on the case in which two atoms interact with a common single-mode thermal field and the maximal entanglement can be obtained only when the atomic transition frequency is highly detuned from the field frequency.

Recently, considerable attentions have been paid to the coupled-cavity system [20–26], which is promising to overcome the difficulty of individual addressability existing in a single cavity. Dynamics in a coupled-cavity array offers a basic setting for distributed quantum information processing and can be studied for a wide range of parameters, such as atom-cavity detuning, intercavity coupling rate, etc. In this paper, we investigate the entanglement dynamics for two atoms trapped in two coupled cavities, each containing one single-mode thermal field.

Contrary to previous studies in which two atoms simultaneously interact with only one single-mode thermal field, here we consider a quantum system comprising two identical two-level atoms trapped in two coupled cavities, each of which is initially in a thermal state. The entanglement dynamics of the atomic system depends upon the photon hopping strength, the detuning between atomic transition frequency and field frequency, and the initial state. We find that even when the atoms symmetrically and resonantly interact with the local thermal fields, the maximally entangled state for the atoms can be generated with the initial state in which one atom is in the ground state and the other is in the excited state. This result is obviously different from the case that two atoms symmetrically and resonantly interact with a common thermal field [4], in which the obtainable entanglement is rather low. Under certain conditions, the thermal fields can induce the periodical entanglement sudden birth and death when the atoms are both initially in excited states or ground states. Remarkably, the peaks of the concurrence do not decrease monotonically when the evolution time increases, which

is distinguished from previous examples [27–30]. By choosing appropriate photon hopping strength and detuning between the atomic transition and the cavities, one can freeze the entanglement between the two atoms when they are initially in the maximally entangled state, which may have practical application in quantum memory and quantum storage [31–33]. The influences of atomic spontaneous emission and photon leakage out of the cavity are analyzed.

2. The Theoretical Model

The coupled-cavity system under consideration is shown in Fig. 1. Two identical two-level atoms 1 and 2 are trapped in two coupled cavities, each containing a single-mode thermal field ρ_{f_i} ($i = 1, 2$). In the frame rotating at the cavity frequency, the total Hamiltonian under the rotating-wave approximation is ($\hbar = 1$):

$$H = \sum_{i=1}^2 \left[\delta_i a_i^\dagger a_i + g_i (S_i^+ a_i + S_i^- a_i^\dagger) \right] + J(a_1^\dagger a_2 + a_1 a_2^\dagger), \quad (1)$$

where $S_i^+ = |e_i\rangle\langle g_i|$ and $S_i^- = |g_i\rangle\langle e_i|$ with $|e_i\rangle$ and $|g_i\rangle$ being the excited state and ground state of the i th atom. a_i^\dagger and a_i are the creation and annihilation operators for the i th thermal field, g_i describes the coupling strength between the i th atom and the i th thermal field, and δ_i is the detuning between the atomic transition and the local cavity mode. J represents the coherent photon hopping strength between the two cavities.

The density operator of the i th thermal radiation field is described by

$$\rho_{f_i} = \sum_{n_i=0}^{\infty} P_i(n_i) |n_i\rangle\langle n_i|, \quad (2)$$

$$P_i(n_i) = \frac{\bar{n}_i^{n_i}}{(\bar{n}_i+1)^{(n_i+1)}}, \quad (3)$$

where $\bar{n}_i = (e^{\hbar w_{f_i}/k_B T_i} - 1)^{-1}$ is the mean photon number and $|n_i\rangle$ is the Fock state. k_B is the Boltzmann constant, w_{f_i} is the frequency of the cavity mode, and T_i is the temperature.

The excitation number of the total system is conserved during the state evolution since the excitation number operator $\hat{N} = \sum_{i=1}^2 (|e_i\rangle\langle e_i| + a_i^\dagger a_i)$ commutes with the Hamiltonian H . For different initial excitation numbers, the system will evolve in different invariant subspaces. The zero-excitation subspace is:

$$\Gamma_0 = \{|g_1 g_2\rangle |0\rangle_1 |0\rangle_2\}, \quad (4)$$

and the single-excitation subspace is:

$$\begin{aligned} \Gamma_1 = \{ & |e_1 g_2\rangle |0\rangle_1 |0\rangle_2, |g_1 e_2\rangle |0\rangle_1 |0\rangle_2, \\ & |g_1 g_2\rangle |1\rangle_1 |0\rangle_2, |g_1 g_2\rangle |0\rangle_1 |1\rangle_2\}. \end{aligned} \quad (5)$$

The N -excitation subspace ($N = 2, 3, 4, \dots, \infty$) becomes:

$$\begin{aligned}
\Gamma_N &= \{\Gamma_a, \Gamma_b, \Gamma_c, \Gamma_d\}, \\
\Gamma_a &= \{|e_1g_2\rangle|N-1\rangle_1|0\rangle_2, |e_1g_2\rangle|N-2\rangle_1|1\rangle_2, \dots, \\
&\quad |e_1g_2\rangle|1\rangle_1|N-2\rangle_2, |e_1g_2\rangle|0\rangle_1|N-1\rangle_2\}, \\
\Gamma_b &= \{|g_1e_2\rangle|N-1\rangle_1|0\rangle_2, |g_1e_2\rangle|N-2\rangle_1|1\rangle_2, \dots, \\
&\quad |g_1e_2\rangle|1\rangle_1|N-2\rangle_2, |g_1e_2\rangle|0\rangle_1|N-1\rangle_2\}, \\
\Gamma_c &= \{|g_1g_2\rangle|N\rangle_1|0\rangle_2, |g_1g_2\rangle|N-1\rangle_1|1\rangle_2, \dots, \\
&\quad |g_1g_2\rangle|1\rangle_1|N-1\rangle_2, |g_1g_2\rangle|0\rangle_1|N\rangle_2\}, \\
\Gamma_d &= \{|e_1e_2\rangle|N-2\rangle_1|0\rangle_2, |e_1e_2\rangle|N-3\rangle_1|1\rangle_2, \dots, \\
&\quad |e_1e_2\rangle|1\rangle_1|N-3\rangle_2, |e_1e_2\rangle|0\rangle_1|N-2\rangle_2\}.
\end{aligned} \tag{6}$$

Suppose the density operator of the whole system is initially $\rho(0)$. After an interaction time the density operator is given by $\rho(t) = e^{-iHt}\rho(0)e^{iHt}$. Taking a partial trace over two thermal fields, we can obtain the reduced density matrix for two atoms which is spanned in the basis $\{|e_1e_2\rangle, |e_1g_2\rangle, |g_1e_2\rangle, |g_1g_2\rangle\}$. Without any initial coherences from both the atoms and fields, we calculate the reduced density matrix in each excitation subspace, then sum over all the subspaces to get the total reduced density matrix (7). The used Hilbert space is cut off at $N \sim 5(\bar{n} + 1)$. For example, when $\bar{n} = 0.1$, the Hilbert space is cut off at $N = 5$; when $\bar{n} = 1$, the Hilbert space is cut off at $N = 15$; when $\bar{n} = 10$, the Hilbert space is cut off at $N = 60$. Therefore, the density matrix ρ_a has a simple form:

$$\rho_a = \begin{pmatrix} A & 0 & 0 & G \\ 0 & B & E & 0 \\ 0 & E^* & C & 0 \\ G^* & 0 & 0 & D \end{pmatrix}. \tag{7}$$

The values of the elements in Eq. (7) depend on the initial state of the whole system and they can be explicitly calculated by numerical simulation. We adopt the Wootters's [34] concurrence $C(\rho_a)$ to quantify the entanglement for two atoms, which is defined as

$$C(\rho_a) = \max \left\{ 0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4} \right\}, \tag{8}$$

where $\lambda_1, \lambda_2, \lambda_3$ and λ_4 are the eigenvalues arranged in decreasing order of the following matrix

$$\xi = \rho_a(\sigma_y \otimes \sigma_y)\rho_a^*(\sigma_y \otimes \sigma_y), \tag{9}$$

where ρ_a^* represents the complex conjugation of ρ_a and σ_y is the corresponding Pauli matrix. Therefore the concurrence for the two atoms takes the form:

$$C(\rho_a) = 2 \max \left\{ 0, |E| - \sqrt{AD}, |G| - \sqrt{BC} \right\}. \tag{10}$$

It has been shown that using the concurrence to deal with the mixed state of any two qubits is an easy evaluation of entanglement of formation, and it satisfies the following important conditions of the measure of entanglement: (1) $C(\rho_a) = 0$ if and only if ρ_a is separable; (2) For all local unitary transformations, $C(\rho_a)$ keeps invariant; (3) $C(\rho_a)$ does not increase under local general measurements, classical communications, and post-selection of subensemble. For unentangled atoms $C(\rho_a) = 0$, while $C(\rho_a) = 1$ for the maximally entangled state. Although the exact analytic expression for Eq. (10) is very complicated as the excitation number becomes infinite, there are several limiting situations where the whole dynamics can be simplified. Under these limiting conditions, we can obtain an effective Hamiltonian that reflects the essentially physical processes and provides a basic explanation for the numerical results.

3. Generation of Atomic Entanglement

Assume that the initial state for the two atoms is $|e_1 g_2\rangle$. Then the density matrix of the whole system is

$$\rho(0) = |e_1 g_2\rangle\langle e_1 g_2| \otimes \sum_{n_1, n_2=0}^{\infty} P_1(n_1) P_2(n_2) |n_1 n_2\rangle\langle n_1 n_2|. \quad (11)$$

Set $\bar{n}_1 = \bar{n}_2 = \bar{n} = 1$, the concurrence is plotted for the cases of large frequency detuning and large hopping strength in Fig. 2 and Fig. 3, respectively. In order to explain the underlying physics explicitly, we introduce two delocalized bosonic modes b_1 and b_2 , which are defined as $b_1 = (a_1 + a_2)/\sqrt{2}$ and $b_2 = (a_1 - a_2)/\sqrt{2}$. We first consider the symmetric coupling situation, i.e., $g_1 = g_2 = g$, and set $\delta_1 = \delta_2 = \delta$ for simplicity. In terms of the new operators, the Hamiltonian H can be rewritten as follows:

$$H = \delta'_1 b_1^\dagger b_1 + \delta'_2 b_2^\dagger b_2 + \frac{g}{\sqrt{2}} \left[b_1 (S_1^+ + S_2^+) + b_2 (S_1^+ - S_2^+) + H.c. \right], \quad (12)$$

where $\delta'_1 = (\delta + J)$ and $\delta'_2 = (\delta - J)$, which indicates that the frequencies of two delocalized field modes are shifted from the cavity frequency due to coherent photon hopping. In the interaction picture with respect to $H_0 = \delta'_1 b_1^\dagger b_1 + \delta'_2 b_2^\dagger b_2$, we get the atom-field interaction Hamiltonian

$$H_I = \frac{g}{\sqrt{2}} \left[e^{-i\delta'_1 t} b_1 (S_1^+ + S_2^+) + e^{-i\delta'_2 t} b_2 (S_1^+ - S_2^+) + H.c. \right]. \quad (13)$$

Under the conditions $\delta'_1 \gg \sqrt{\bar{n}_1 + 1}g/\sqrt{2}$ and $\delta'_2 \gg \sqrt{\bar{n}_2 + 1}g/\sqrt{2}$, there is no energy exchange between the atomic system and the field modes, and the two atoms are coupled to each other via exchange of virtual photons. Then the effective Hamiltonian is given by [20, 35]:

$$H_{eff} = - \sum_{i=1}^2 \left[\left(\frac{g^2}{2\delta'_1} b_1^\dagger b_1 + \frac{g^2}{2\delta'_2} b_2^\dagger b_2 \right) (|e_i\rangle\langle e_i| - |g_i\rangle\langle g_i|) + \lambda |e_i\rangle\langle e_i| + \lambda' (S_1^+ S_2^- + H.c.) \right],$$

(14)

where $\lambda = \frac{g^2}{2\delta_1'} + \frac{g^2}{2\delta_2'}$ and $\lambda' = \frac{g^2}{2\delta_1'} - \frac{g^2}{2\delta_2'}$. The evolution of the atomic system is $\cos(\lambda't)|e_1g_2\rangle - i\sin(\lambda't)|g_1e_2\rangle$, which is independent of the field states. We here have discarded the trivial common phase factor $e^{-i\lambda't}$. Therefore, for large photon hopping strength the local resonant thermal fields can induce maximal atomic entanglement, which is distinguished from the case for two atoms interacting commonly with one single-mode thermal field [4]. The effective Hamiltonian (14) is valid under the condition that the difference between δ and J is much larger than g . When $\delta \sim J$, the eigenfrequency of the normal delocalized mode b_2' approaches the atomic transition frequency so that the atoms can exchange energy with this delocalized mode and the effective Hamiltonian (14) is invalid. This leads to the atom-cavity entanglement and deteriorates the atom-atom entanglement, which accounts for the appearance of the dips in Fig. 2 and Fig. 3 for δ near J . In the regime $\delta \sim J$, the atom-cavity system undergoes Rabi oscillations, and each atom is not only entangled with each other but also with the cavity modes. One can maximize the atom-atom entanglement by choosing the optimal ratio of g to δ_2' and t . The entanglement is very sensitive to the ratio δ_2'/g . This accounts for the maxima and abrupt changes of the concurrence inside the dips of Fig. 2 and Fig. 3. Due to the spread of the Rabi frequencies corresponding to different photon numbers, the atoms cannot be completely disentangled with the cavity modes and the maximal atom-atom entanglement cannot be obtained. In fact, the physics discussed here is similar to that discussed in Ref. [35] which proposed the generation of maximally entangled states for two atoms via dispersive interaction with a single cavity mode.

When two atoms are both initially in their excited states $|e_1e_2\rangle$, we find that the atomic entanglement could also be induced by two thermal fields with appropriate parameters, as shown in Fig. 4. In the case of Fig. 4(a), the atomic entanglement arises from either atom's emission of one photon into the same cavity modes. When the probability for this event is zero, the entanglement vanishes. In Fig. 5, we plot the expectation value of total atomic excitation number $\langle\sigma_{z1} + \sigma_{z2}\rangle$ versus gt for the same parameters as Fig. 4(a). The result shows the peak of concurrence coincides with the case when $\langle\sigma_{z1} + \sigma_{z2}\rangle$ is nearest to zero, which corresponds to the regime where probability for either atom's emission of one photon is maximized. Interestingly, for symmetric atom-cavity couplings the entanglement exhibits periodical sudden birth and death when the atomic transition is slightly detuned from at least one delocalized mode, as shown in Fig. 4(a). Note that the atoms start from a product state, which is distinguished from the previous studies of entanglement sudden birth and death in which the atoms start from an entangled state [28–30]. The duration of the entanglement death is much longer than that of the entanglement life. Unlike previous examples, the peaks of the concurrence do not decrease monotonically as the interaction time increases. The entanglement dynamics for the initial state $|g_1g_2\rangle$ is similar with that

for initial state $|e_1e_2\rangle$, as shown in Fig. 4(b). The entanglement dynamics for both the initial states $|e_1e_2\rangle$ and $|g_1g_2\rangle$ is similar to the case when the two atoms interact with a common cavity mode [4, 5]. On the other hand, for asymmetric atom-cavity couplings, i.e., $g_1 \neq g_2$, the atomic entanglement can be generated when the atoms resonantly interact with two thermal fields, as shown in Fig. 4(c). The vanishes of entanglement in Fig. 4 corresponds to entanglement sudden death that also appears in the system with two atoms independently interact with the respective cavities [28]. The considered system involves four subsystems so that the whole system evolution is very complex and does not exhibit periodical features. This accounts for the fact that distributions of peaks and dips in Fig. 3 and Fig. 4 are somewhat random.

4. Freeze of Atomic Entanglement

Moving forward, we also investigate the system evolution when the atoms are initially in the maximally entangled state $|\Psi_m\rangle = (|e_1g_2\rangle + |g_1e_2\rangle)/\sqrt{2}$. In the resonant interaction situation, as shown in Fig. 5, for $J \gg g$, the entanglement can be frozen. This is due to the fact in this case the conditions $\delta'_1 \gg \sqrt{\bar{n}_1 + 1}g/\sqrt{2}$ and $\delta'_2 \gg \sqrt{\bar{n}_2 + 1}g/\sqrt{2}$ are satisfied, so that the effective Hamiltonian of Eq. (14) dominates the system evolution and the maximally entangled state $|\Psi_m\rangle$ becomes an eigenstate of this effective Hamiltonian. As the values of J/g decreases, the concurrence decreases. Especially when $J/g \rightarrow 0$, the sudden death of entanglement emerges, since in this case each atom independently interacts with a thermal field, which causes the leakage of the atomic coherence into the fields.

The influence of temperature, i.e., mean photon numbers \bar{n} , on the atom-atom entanglement are taken into consideration, as plotted in Fig. 7. The result shows that the larger the mean photon number, the smaller the concurrence. This phenomenon can be understood in the following way. The probability that the atoms exchange energy with the fields increases with mean photon numbers. When the photon numbers are large, the conditions $\delta'_1 \gg \sqrt{\bar{n}_1 + 1}g/\sqrt{2}$ and $\delta'_2 \gg \sqrt{\bar{n}_2 + 1}g/\sqrt{2}$ are not satisfied and the effective Hamiltonian (14) is not valid. When the photon number is sufficiently small so that the effective Hamiltonian (14) is valid, the effective atom-atom coupling strength is $\lambda' = g^2/J = 0.1g$, which is photon-number-independent. When $\lambda't = \pi/4$, i.e., $gt = 2.5\pi$, the excitation is approximately equally shared by the two atoms and the concurrence reaches the maxima. At the time $t = \pi/(2\lambda') = 5\pi$, the excitation is completely transferred from the first atom to the second one. So that the concurrence vanishes.

5. Atomic Entanglement Dynamics with Dissipation Being Included

In all the above discussions, we have just supposed that the entire system is ideally isolated from the outside environment. Taking cavity decay and atomic spontaneous emission into

account, the master equation for the density matrix $\rho(t)$ of the system can be expressed as:

$$\begin{aligned}
\dot{\rho}(t) = & -i[H, \rho(t)] \\
& + \frac{\kappa}{2}(\bar{n} + 1) \sum_{i=1}^2 [2a_i \rho(t) a_i^\dagger - a_i^\dagger a_i \rho(t) - \rho(t) a_i^\dagger a_i] \\
& + \frac{\kappa}{2}\bar{n} \sum_{i=1}^2 [2a_i^\dagger \rho(t) a_i - a_i a_i^\dagger \rho(t) - \rho(t) a_i a_i^\dagger] \\
& + \frac{\gamma}{2}(\bar{n} + 1) \sum_{i=1}^2 [2S_i^- \rho(t) S_i^+ - S_i^+ S_i^- \rho(t) - \rho(t) S_i^+ S_i^-] \\
& + \frac{\gamma}{2}\bar{n} \sum_{i=1}^2 [2S_i^+ \rho(t) S_i^- - S_i^- S_i^+ \rho(t) - \rho(t) S_i^- S_i^+], \tag{15}
\end{aligned}$$

where κ and γ denote the cavity decay rate and the atomic spontaneous emission rate, respectively. The dependence of the concurrence on the cooperative parameter $C_{\kappa\gamma} = g^2/(\kappa\gamma)$ is plotted, as shown in Fig. 8. When the detunings between atomic transition and the delocalized modes are much larger than the atom-cavity coupling strength, the entanglement dynamics is much more sensitive to the atomic decay than to the cavity loss as in this case the cavity modes are only virtually excited and they are decoupled from the atomic entanglement dynamics. Therefore, the scheme is favorable when $\gamma \ll \kappa$. Here we choose $\gamma = 0.1\kappa$ in Fig 8(a) and (c), and $\gamma = \kappa$ in Fig 8(b) and (d). The difference between Fig 8(a)((c)) and Fig 8(b)((d)) is that the concurrence decreases quickly as the atomic decay increases, which demonstrates the cavity decay is not the dominant factor deteriorating the entanglement.

6. Conclusions

In conclusion, we have studied the entanglement dynamics of two identical atoms interacting with two single-mode thermal fields based on the coupled-cavity system. The atom-atom concurrence is calculated under various conditions. The results show that the entanglement behaviors depend upon the photon hopping strength, the atom-cavity detuning, and the initial atomic state. It is demonstrated that under the situation where each atom is resonant with the local field mode, the maximal entanglement for two atoms can be generated with one atom in the ground state and the other in the excited state initially, which is impossible for the case with two atoms interacting with a single thermal cavity mode. When the two atoms are both initially in the excited state, the entanglement sudden birth and death occur periodically, and the peaks of the concurrence do not decrease monotonically when the evolution time increases. Furthermore, we show that the initial two-atom maximal entanglement can be frozen with suitable choice of the parameters. The effect of dissipation on the entanglement is analyzed.

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List of Figure Captions

Fig. 1. (Color online) The proposed experimental setup. Two two-level atoms are respectively trapped in two coupled cavities, each of which is initially in a thermal state.

Fig. 2. (Color online) Atom-atom concurrence as a function of the evolution time and photon hopping strength with $\bar{n} = 1$ and $\delta = 10g$. The atoms are initially in the state $|e_1g_2\rangle$.

Fig. 3. (Color online) Atom-atom concurrence as a function of the evolution time and photon hopping strength with $\bar{n} = 1$ and $J = 25g$. The atoms are initially in the state $|e_1g_2\rangle$.

Fig.4. (Color online) Atom-atom concurrence as a function of the evolution time and hopping strength when $\bar{n} = 0.1$: (a) $g_1 = g_2 = g$ for the initial state $|e_1e_2\rangle$; (b) $g_1 = g_2 = g$ for the initial state $|g_1g_2\rangle$; (c) $\delta = 0$, $g_1 = J$ and $g_2 = g$ for the initial state $|e_1e_2\rangle$.

Fig.5. (Color online) Dash red line represents the atomic population inversion $\langle\sigma_{z1} + \sigma_{z2}\rangle$ and solid black line represents the average photon number $\langle a_1^\dagger a_1 \rangle$, which are as a function of the evolution time when $\bar{n} = 0.1$, $J = 20g$ and $\delta = 18.5g$ for the initial state $|e_1e_2\rangle$.

Fig.6. (Color online) Atom-atom concurrence as a function of evolution time and hopping strength with $\delta = 0$ and $\bar{n} = 0.1$. The atoms are initially in the entangled state $(|e_1g_2\rangle + |g_1e_2\rangle)/\sqrt{2}$.

Fig.7. (Color online) Atom-atom concurrence as a function of evolution time with $\delta = 0$, $J = 10g$. The atoms are initially in: (a) $|e_1g_2\rangle$; (b) $(|e_1g_2\rangle + |g_1e_2\rangle)/\sqrt{2}$.

Fig.8. (Color online) Atom-atom concurrence as a function of the evolution time gt and cooperative parameter $C_{\kappa\gamma}$ when $\bar{n} = 0.1$. The atoms are in the initial state $|e_1g_2\rangle$ with $\delta = 0$ and $J = 10g$: (a) $\gamma = 0.1\kappa$; (b) $\gamma = \kappa$. While the atoms are in the initial state $(|e_1g_2\rangle + |g_1e_2\rangle)/\sqrt{2}$ with $\delta = 15g$ and $J = 5g$: (c) $\gamma = 0.1\kappa$; (d) $\gamma = \kappa$.

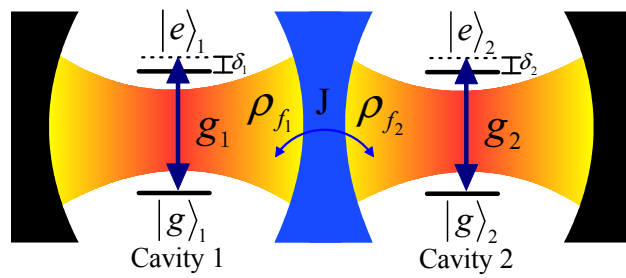


Fig. 1.

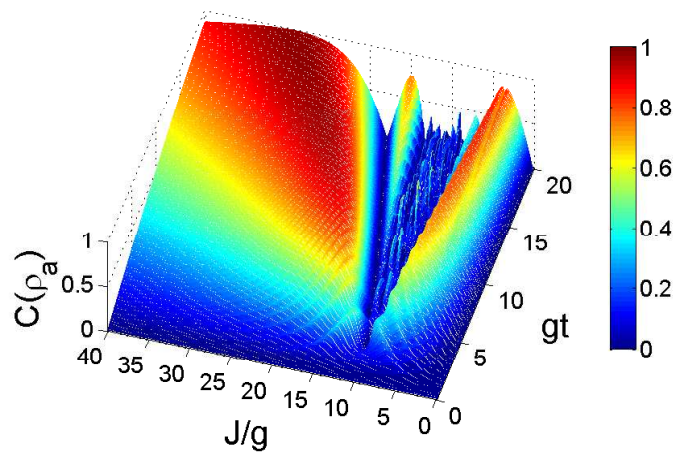


Fig. 2.

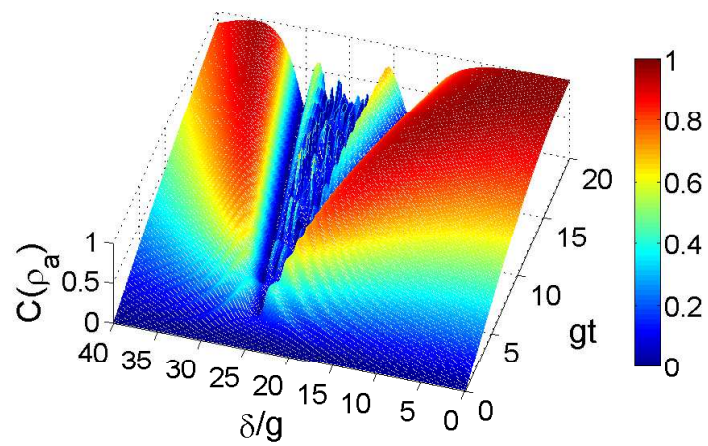
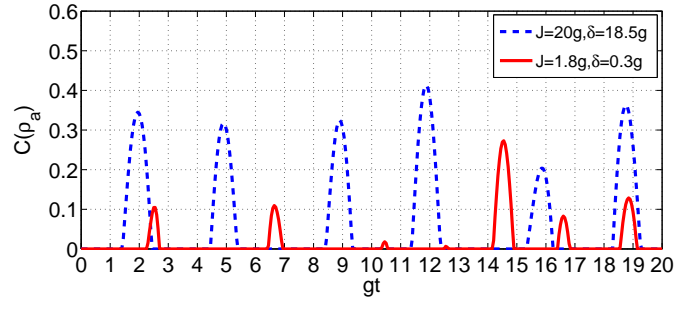
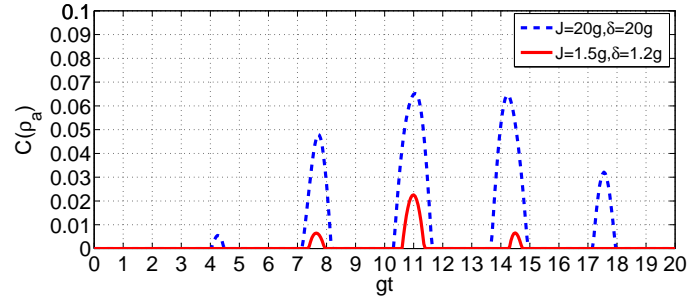


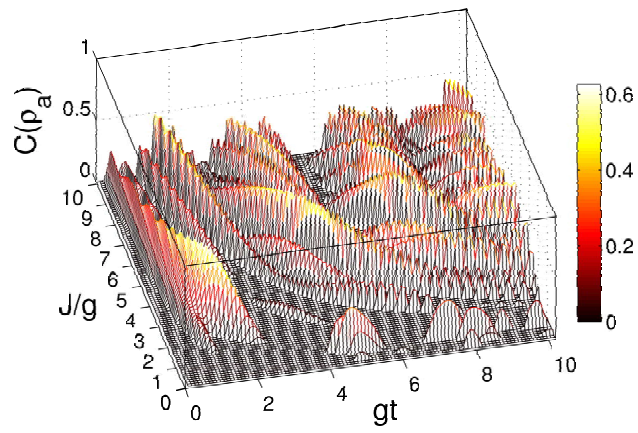
Fig. 3.



(a)



(b)



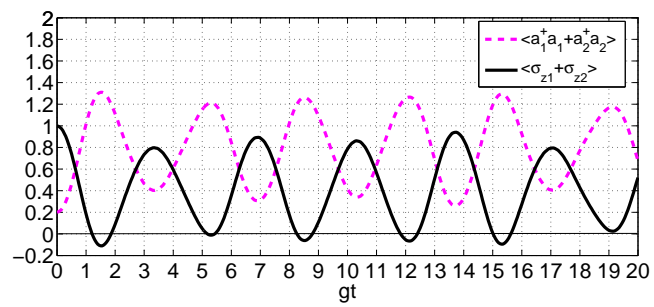


Fig. 5.

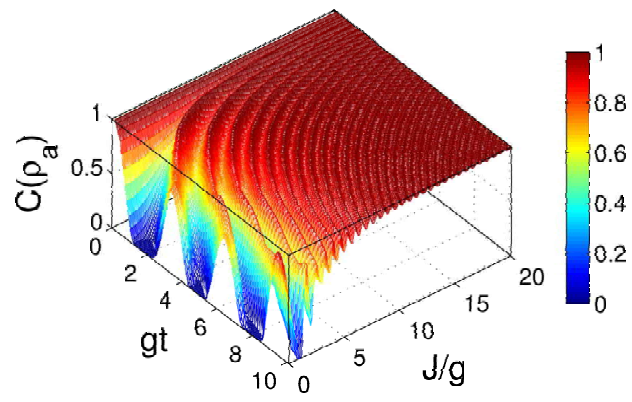
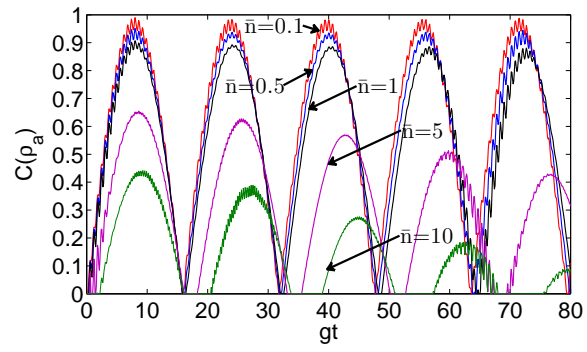
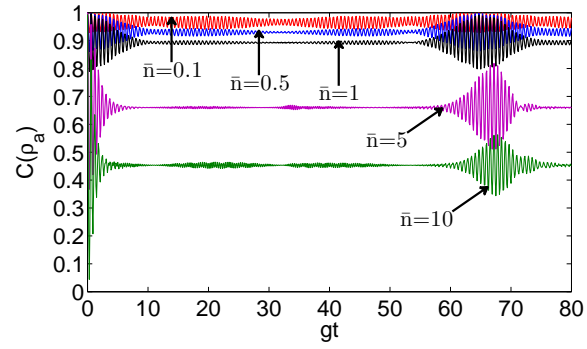


Fig. 6.

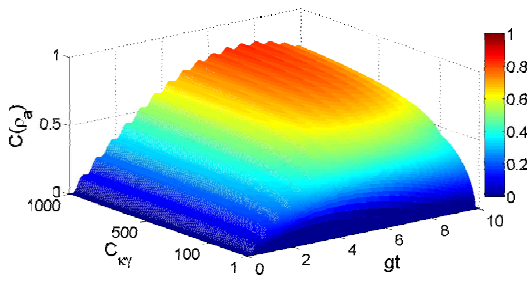


(a)

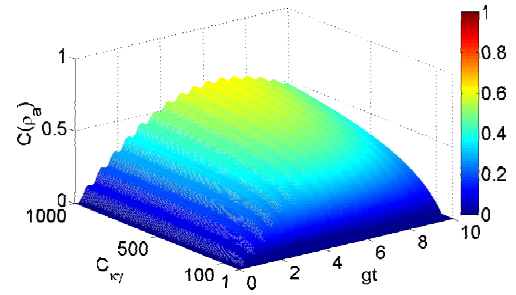


(b)

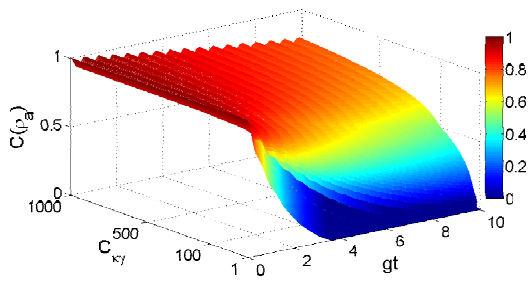
Fig. 7.



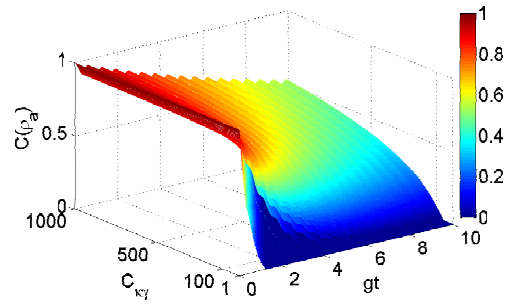
(a)



(b)



(c)



(d)

Fig. 8.